Characterization of Mesoscale Predictability

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Grant Number: N00014-11-1-0331
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LONG-TERM GOALS

One of the major efforts in the atmospheric sciences has been to develop and implement high-resolution forecast models and to improve their parameterization of unresolved physical processes (boundary-layer transport, cloud microphysics…). For the last three decades, the relatively pessimistic predictions of Lorenz (1969) about the predictability of small-scale (i.e., mesoscale) atmospheric features have been largely ignored as routine weather forecasts were conducted at increasingly fine scale. Recent research suggests there are nevertheless, significant limitations to the predictability of mesoscale atmospheric circulations. Our goal is to develop an understanding of the predictability of such circulations in forecasts generated by state-of-the-art high-resolution mesoscale models.

OBJECTIVES

Specific questions addressed in our research include:

1. How commonly does rapid growth of initial errors occur in mesoscale meteorological settings?
2. How sensitive are these results to different strategies for developing the initial ensemble spread using the ensemble Kalman filter?
3. How can ensemble forecasts be best used to identify and help predict these difficult events?

The answers to these questions are of direct benefit to Navy forecasters using COAMPS to produce aviation and other forecasts of mesoscale phenomena.

APPROACH

The P.I. and graduate student Matt Gingrich, together with Drs. James Doyle and P. Alex Reinecke of NRL, are using the COAMPS model to conduct 100-member ensemble simulations of high impact events. Under previous support we considered downslope windstorms (Reinecke and Durran, 2009), which, it had been argued, had high mesoscale predictability. More recently, we have considered the prediction of lowland snow in the Puget Sound lowlands. Both of theses weather phenomenon have exhibited high sensitivity to initial conditions in the sense that the spread within a large initial ensemble (either 70 or 100 members) grew vary rapidly over time scales much shorter than anticipated.

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Characterization of Mesoscale Predictability**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Department of Atmospheric Sciences,Box 351640,Seattle,WA,98195-1640**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Part of the motivation for this effort is to help inform the community of the need to move beyond deterministic mesoscale forecasts, which despite all the talk about ensemble prediction, are still the backbone of military, civilian and private meteorological forecasts.

WORK COMPLETED

Our paper "Large-Scale Errors and Mesoscale Predictability in Pacific Northwest Snowstorms" (written in collaboration with James Doyle and Alex Reinecke), was published in the *Journal of the Atmospheric Sciences*. A second paper, "Mesoscale Predictability and Initial-Condition Error Growth in Two East-Coast Snowstorms" by graduate student Mark Gingrich, the P.I. and Alex Reinecke has been submitted to the *Journal of the Atmospheric Sciences*. Mark also presented these results at the American Meteorological Society conference on Mesoscale Meteorology last August in Portand, Oregon. In addition, we have obtained as yet unpublished results connecting the spread in ensemble errors due to initial condition uncertainty with error growth in the classical turbulence-model theory of predictability proposed by Lorenz (1969).

RESULTS

The growth of mesoscale forecast errors arising from uncertainties in initial conditions was investigated by examining 100-member ensemble forecasts of two powerful snowstorms that struck the East Coast of the United States in February and December 2010. The ensemble spreads for both storms revealed significant forecast uncertainties in the snow-water equivalent precipitation (SWE), the total precipitation, and the 850-hPa temperature at lead times as short as 18 hours. These uncertainties arose from mesoscale variations in the position of the rain-snow line or the heavy precipitation regions that were in turn linked to variations among the ensemble members in large-scale fields such as the sea level pressure.

In the February case, significant uncertainties in the forecast precipitation type developed over parts of North Carolina and Virginia due to differences in how each ensemble member simulated the interactions between extant cold air damming and the warm front of an approaching coastal cyclone. Ensemble members with low-pressure centers farther to the south predicted colder temperatures over the rain/snow transition region and higher snowfall. In the vicinity of Richmond, Virginia, the difference in forecast SWE between the means of the 17 lowest- and 17 highest-snowfall members exceeded a factor of two beginning at forecast lead times of 18 hours. At the end of the 36-hour forecast, the difference between the low- and high-subset mean accumulated SWE was 25 kg m^{-2}, whereas the differences in total precipitation were just 15 kg m^{-2} , indicating that the primary difference was not in overall storm intensity, but rather in the difference between rain and snow (Fig. 1).

In the December case, large uncertainties in snow, total precipitation, and 850-hPa temperatures were related to a significant uncertainty in the track of the cyclone. As shown in Fig.~2, those ensemble members that kept the low farther west tended to produce warmer temperatures and more precipitation and snow over southeast New England. The difference between the 850-hPa temperatures of the means of the 17 warmest and 17 coldest ensemble members above Providence, Rhode Island was approximately 8°C at a forecast lead time of 18 hours.

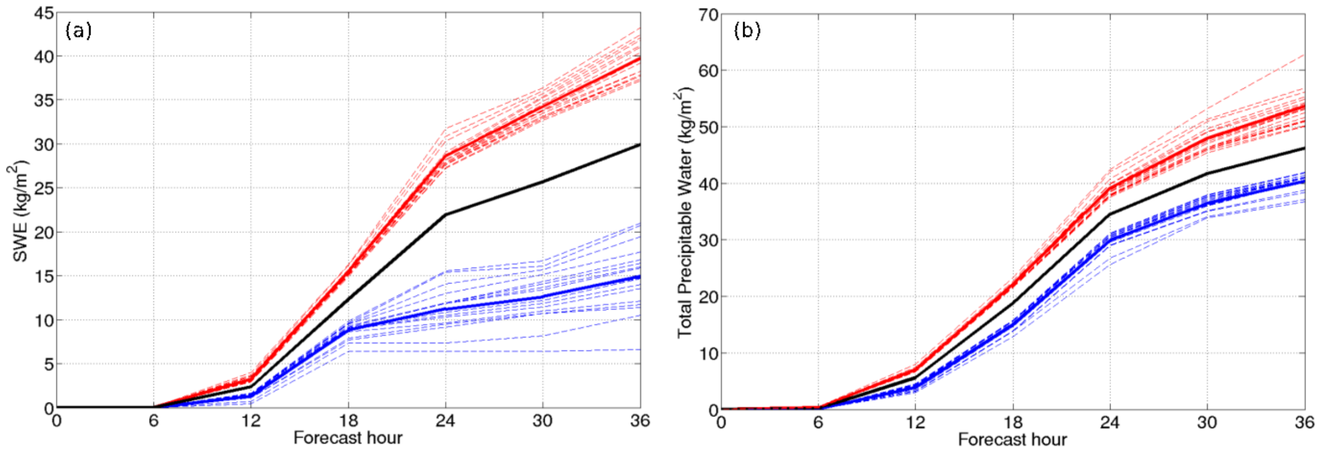

Figure 1: 36-hour accumulated (a): SWE and (b): Total precipitable water over Richmond between 12 UTC 5 February and 00 UTC 7 February for the highest (red) and lowest (blue) 17 ensemble members and their means. The full ensemble mean is shown in black. Note the difference in the vertical scales.

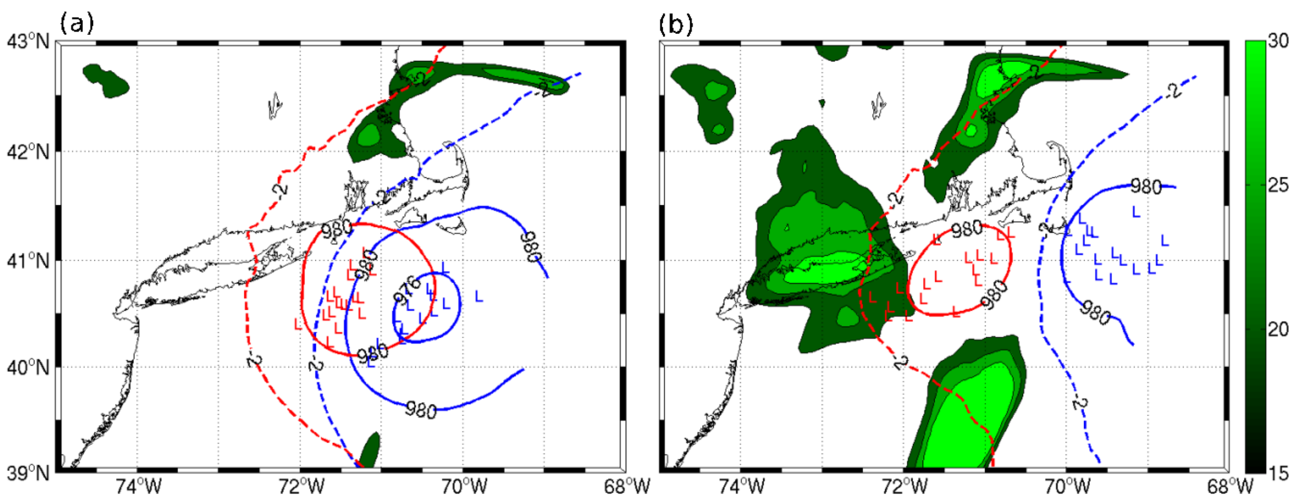

Figure 2: Locations of the -2 °C 850 hPa isotherms, 980 and 976 hPa SLP isobars, and low centers valid 06 UTC 6 February, subset by the 850 temperature: (a) 18-hour forecast initialized 12 UTC 26 December, and (b) 30-hour forecast initialized 00 UTC 26 December at Providence. Red corresponds to the warmest 17 members, and blue the coldest 17 members. Contoured in green is the warm-subset-mean minus cold-subset-mean difference in total accumulated precipitation between 12 UTC 26 December and 12 UTC 27 December. Shown are the 20, 25, and 30 kg m^{-2} lines in (b). In (a), the 30 kg m^{-2} line is not applicable.

One key question is whether the rate at which the spread in our ensemble grows correctly represents the rate at which slightly different atmospheric states would diverge. Evaluating the consistency of our 22 ensemble forecasts for 850-hPa temperatures within a large region east of the Appalachians at an 18-hour lead time, we obtained rank histogram and binned spread skill plots illustrating that the

variance of the error in the ensemble mean was greater than the predicted ensemble spread. Therefore, our ensemble was, on average, under-dispersive, and the ensemble spread likely underestimated the true forecast uncertainty.

Many studies have aimed to elucidate the error growth dynamics controlling mesoscale predictability. Important early theories were based on an inverse error cascade in classical turbulence models, where unresolved small-scale errors gradually propagated up to the largest scales Lorenz (1969). In contrast, the dominant paradigm in operational mesoscale meteorology has been one in which the mesoscale is assumed to inherit predictability from the synoptic scale and thereby maintain forecast skill at much longer lead times than those suggested by turbulence models (Anthes 1985, Mass 2002). Nevertheless, the results in this paper, along with several recent studies (Nuss and Miller 2001, Reinecke and Durran 2009, Durran et al. 2013), suggest that mesoscale circulations are in fact extremely sensitive to small synoptic-scale errors. A variety of situations have now been documented in which the degree of synoptic-scale accuracy required to successfully forecast mesoscale weather patterns at one- or two-day lead times would be quite difficult to achieve in practice.

Recent studies have suggested that forecast errors amplify by projecting onto the most rapidly growing physical structures, the scale of which depends on the model resolution and the dynamics of the flow being modeled. Examples include baroclinic instability on the synoptic scale (Tribbia and Baumhefner 2004) and convective instability on the small scale (Hohenegger and Schär 2007). Linking instabilities with upscale error growth, (Tan et al. 2004; Zhang et al. 2007) suggested a multistage process in which errors originating on the scale of moist convection are responsible for stimulating error growth at intermediate scales that subsequently spread to scales large enough to influence baroclinic instability.

The spectral structure of the ensemble spread in these simulations was examined by evaluating the ensemble- and meridional-averaged total and perturbation kinetic energy spectra on the 5-km, convection-permitting grid. The ensembles clearly captured the observed $k^{-5/3}$ total kinetic energy spectrum at wavelengths less than approximately 400 km and also showed a transition to a roughly k^{-3} dependence at longer wavelengths. In contrast to the small-scale initial errors assumed in several idealized studies of atmospheric predictability, the initial perturbation kinetic energy of our EnKF-generated ensembles was maximized at the largest scales. This is consistent with previous investigations that relied on data assimilation to either create pairs of different initial conditions (Bei and Zhang 2007, Mapes et al. 2008) or to initialize a large ensemble (Durran et al. 2013), all of which also found that the initial perturbation kinetic energy was maximized at the largest scales. As discussed in Durran et al. (2013), this large-scale maximum is likely a reflection of both small shifts in the structure of the synoptic-scale waves and the true spectral signature of isolated, small-scale disturbances.

At least as notable as the initial structure of the perturbation kinetic energy in our ensembles is the nature of the error growth. As shown in Fig. 3, initial-condition errors did not simply propagate upscale according to an inverse cascade. Instead, the initial errors began growing immediately at all scales, and the amplifying perturbation kinetic energy spectra formed a series of self-similar curves over all wave numbers where the error had not yet saturated. Following the terminology suggested by Mapes et al. (2008), the evolution of the perturbation kinetic energy in Fig.~17 may be described as ``up-magnitude'' rather than ``up-scale''. We are continuing to investigate the factors regulating the structure and evolution of the kinetic energy spectra in our ensembles.

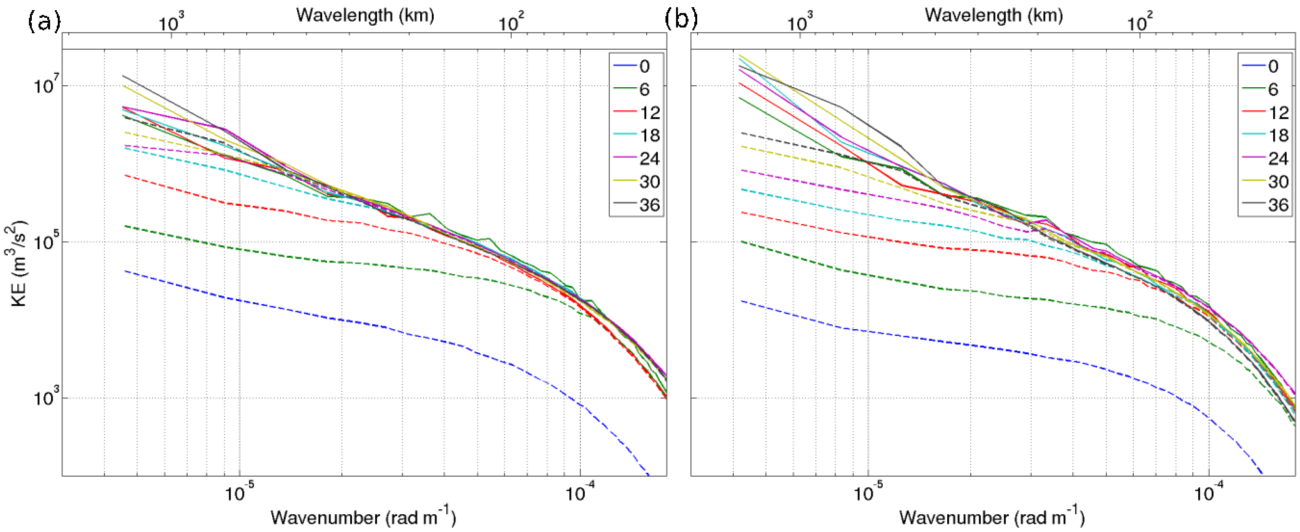

Fig. 3: Ensemble- and meriodional-averaged total (solid lines) and perturbation (dashed lines) kinetic energy spectra at 500 hPa shown every six hours (line colors given in the legend) for the ensemble initialized (a): 12 UTC 4 February and (b): 12 UTC 25 December. Only those wavelengths greater than the 7Δx numerical dissipation scale are shown

IMPACT/APPLICATIONS

Forecasting mesoscale meteorological phenomena is of importance to many naval operations, including those in coastal zones, those involving aviation in complex terrain, and those requiring information about the structure of the planetary boundary layer. Understanding the degree of confidence that can be realistically expected from fine-scale deterministic weather forecasts at various lead times will help meteorologists and other users assess the importance of alternative approaches, such as ensemble forecast systems. The possibility that small initial errors in the large-scale analysis impose a practical limit on mesoscale predictability is a new paradigm that will provide a further impetus wider adoption of the ensemble approach.

RELATED PROJECTS

None

REFERENCES

Anthes, R. A., Y.-H. Kuo, D. P. Baumhefner, R. M. Errico, and T. W. Bettge, 1985: Predictability of mesoscale atmospheric motions. *Adv. Geophys.,* 28, 159–202.

Bei, N. and F. Zhang, 2007: Impacts of initial condition errors on mesoscale predictability of heavy precipitation along the Mei-Yu front of China. *Quart. J. Roy. Meteor. Soc.,* 133, 83–99.

Durran, D.R., P.A. Reinecke, and J.D. Doyle, 2013: Large-Scale Errors and Mesoscale Predictability in Pacific Northwest Snowstorms. *J. Atmos. Sci.,* 70, 1470-1487

Hohenegger, C. and C. Schär, 2007: Atmospheric predictability at synoptic versus cloud- resolving scales. *Bull. Amer. Meteor. Soc.,* 88, 1783–1793.

Mapes, B., S. Tulich, T. Nasuno, and M. Satoh, 2008: Predictability aspects of global aqua- planet simulations with explicit convection. *J. Meteor. Soc. Japan,* 86A, 175–185.

Lorenz, E. N., 1969: The predictability of a flow which possesses many scales of motion. *Tellus,* 21, 289-307.

Mass, C. F., D. Ovens, K. Westrick, and B. A. Colle, 2002: Does increasing horizontal resolution produce more skillful forecasts? *Bull. Amer. Meteor. Soc.,* 83 (3), 407–430.

Nuss, W. and D. Miller, 2001: Mesoscale predictability under various synoptic regimes. *Nonlinear Proc. in Geophys.,* 8 (6), 429–438.

Reinecke, P. A. and D. R. Durran, 2009: Initial-condition sensitivities and the predictability of downslope winds. *J. Atmos. Sci.,* 66 (11), 3401–3418.

Tan, Z.-M., F. Zhang, R. Rotunno, and C. Snyder, 2004: Mesoscale predictability of moist baroclinic waves: Experiments with parameterized convection. *J. Atmos. Sci.,* 61 (14), 1794–1804.

Tribbia, J. and D. Baumhefner, 2004: Scale interactions and atmospheric predictability: An updated perspective. *Mon. Wea. Rev.,* 132 (3), 703–713.

Zhang, F., N. Bei, R. Rotunno, C. Snyder, and C. C. Epifanio, 2007: Mesoscale predictability of moist baroclinic waves: Convection-permitting experiments and multistage error growth dynamics. *J. Atmos. Sci.,* 64 (10), 3579–3594.

PUBLICATIONS

Durran, D.R., P.A. Reinecke, and J.D. Doyle, 2013: Large-Scale Errors and Mesoscale Predictability in Pacific Northwest Snowstorms. *J. Atmos. Sci.,* 70, 1470-1487 [published, refereed]

Gingrich, M.A., D.R. Durran, and P.A. Reinecke, 2013: Mesoscale Predictability and Initial-Condition Error Growth in Two East-Coast Snowstorms. *J. Atmos. Sci.,* submitted.